Integrable Optics Test Accelerator

A.Valishev, S.Nagaitsev (FNAL), V.Danilov (ORNL), D.Shatilov (BINP)

Input from
V.Kashikhin, G.Romanov, L.Nobrega, I.Batalov, H.Witte, A.Seryi

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Proton Accelerators for Science and Innovation Workshop

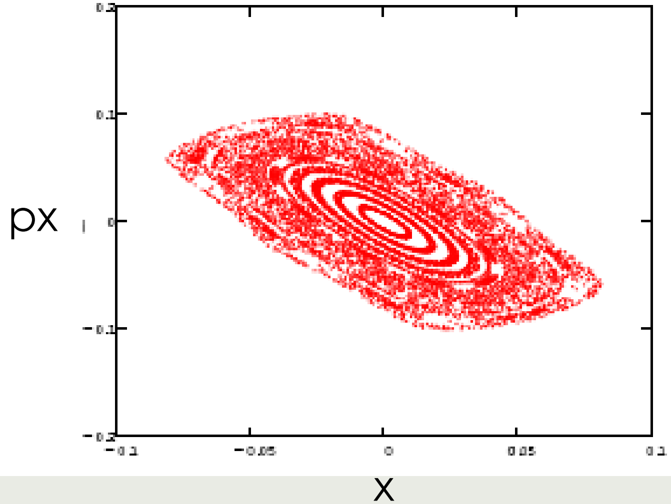
Fermilab

Outline

- Concept of Nonlinear Integrable Optics
  - Nonlinear lattice and potential
  - Maximum nonlinear tune shift
  - Numerical simulations
- IOTA Goals and Scope
- Ring Design
- Status and Plans

Motivation

- The main feature of all present accelerators – linear focusing lattice: particles have nearly identical betatron frequencies (tunes) by design.
  - Hamiltonian has explicit time dependence
  - All nonlinearities (both magnet imperfections and specially introduced) are perturbations and make single particle motion unstable due to resonant conditions



Typical phase space portrait (single octupole lens):

1. Regular orbits at small amplitudes
2. Resonant islands + chaos at larger amplitudes

Motivation

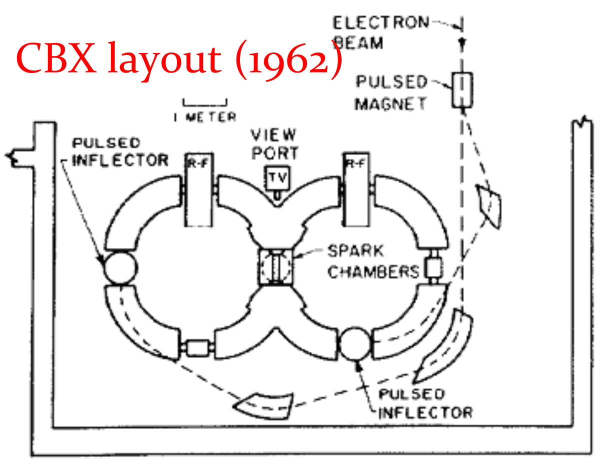
COLLIDING BEAMS: PRESENT STATUS; AND THE SLAC PROJECT*

B. Richter **Report at HEAC 1971**

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

The discovery in the early '60's at the Princeton-Stanford ring of what was thought to be the resistive wall instability brought the realization that circular accelerators are fundamentally unstable devices because of the interaction of the beam with its environment. Stability is achieved only through Landau damping and/or some external damping system.

CBX layout (1962)



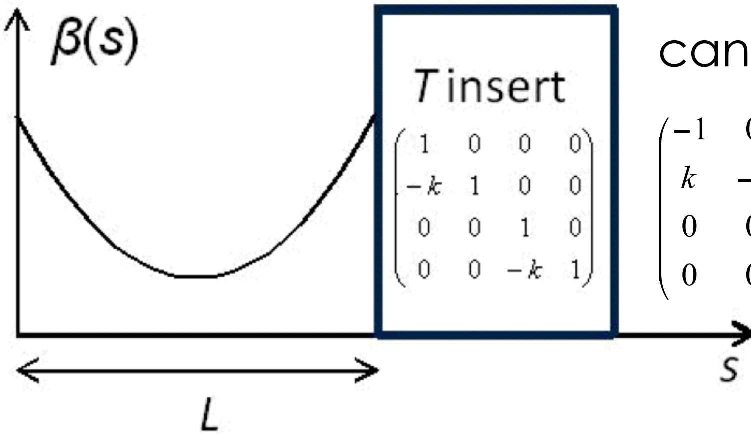
- 1965, Priceton-Stanford CBX: First mention of an 8-pole magnet
  - Observed vertical resistive wall instability
  - With octupoles, increased beam current from ~5 to 500 mA
- CERN PS: In 1959 had 10 octupoles; not used until 1968
  - At 10^{12} protons/pulse observed (1st time) head-tail instability. Octupoles helped.
  - Once understood, chromaticity jump at transition was developed using sextupoles.
  - More instabilities were discovered; helped by octupoles, fb

Do Accelerators Need to be Linear?

- Search for a lattice design that is strongly nonlinear yet stable
  - Orlov (1963)
  - McMillan (1967)
  - Perevedentsev, Danilov (1990)
  - Chow, Cary (1994)
- Nonlinear Integrable Optics: Danilov and Nagaitsev proposed a solution for nonlinear lattice with 2 invariants of motion that can be implemented with special magnets
  - Phys. Rev. ST Accel. Beams 13, 084002 (2010)

Integrable Optics: Time-independence
1st Integral of Motion

- Start with a round axially-symmetric *linear* lattice (FOFO) with the element of periodicity
  - Phase advance $0<\nu_0<0.5\ (2\pi)$ in drift L
  - $n\times0.5$ in T insert
  - $\nu_0+0.5$ total



can be also

$$\begin{pmatrix} -1 & 0 & 0 & 0 \\ k & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & k & -1 \end{pmatrix}$$

- Add special nonlinear potential *V(x,y,s)* in the drift such that
  1. It satisfies the Laplace equation $\Delta V(x,y,s) \approx \Delta V(x,y) = 0$
  2. The Hamiltonian is time-independent in normalized variables

$$H = \frac{p_x^2}{2} + \frac{p_y^2}{2} + K(s)\cdot\left(\frac{x^2}{2} + \frac{y^2}{2}\right) + V(x,y,s) \qquad H_N = \frac{p_{xN}^2 + p_{yN}^2}{2} + \frac{x_N^2 + y_N^2}{2} + U(x_N, y_N, \psi)$$

$$U(x_N, y_N, \psi) = \beta(\psi) V\left(x_N\sqrt{\beta(\psi)}, y_N\sqrt{\beta(\psi)}, s(\psi)\right)$$

H is invariant of motion

Integrable Optics: Special Potential 2nd Integral of Motion

- Find potentials that result in the Hamiltonian having a second integral of motion. In elliptic variables ξ, η

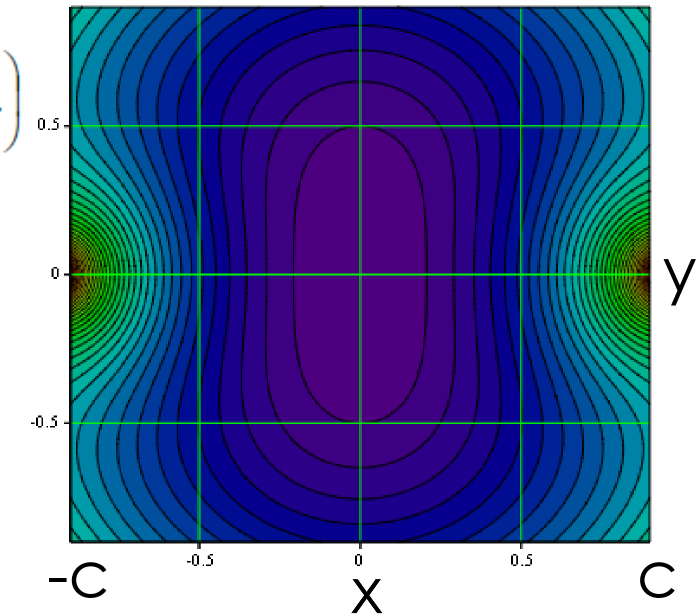
$$U(x,y)=\frac{x^2}{2}+\frac{y^2}{2}+\frac{f_2(\xi)+g_2(\eta)}{\xi^2-\eta^2} \qquad f_2(\xi)=\xi\sqrt{\xi^2-1}\left(d+t\,\mathrm{acosh}(\xi)\right) \quad g_2(\eta)=\eta\sqrt{1-\eta^2}\left(q+t\,\mathrm{acos}(\eta)\right)$$

- Multipole expansion of U for d=0, q=t $\pi/2$ is

$$U(x,y)\approx\frac{x^2}{2}+\frac{y^2}{2}$$
$$+t\,\mathrm{Re}\left((x+iy)^2+\frac{2}{3}(x+iy)^4+\frac{8}{15}(x+iy)^6+\frac{16}{35}(x+iy)^8+\ldots\right)$$

- Theoretical maximum nonlinear tune

  shift per cell is
  - 0.5 for mode 1, **or 50%**
  - 0.25 for mode 2, or 25%



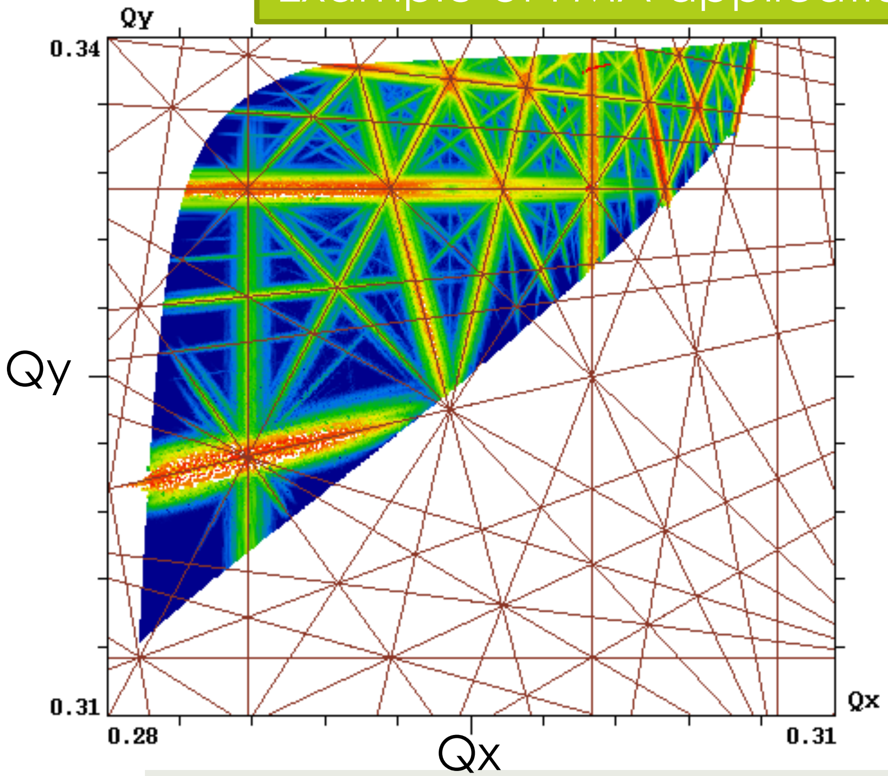
Numerical Simulations

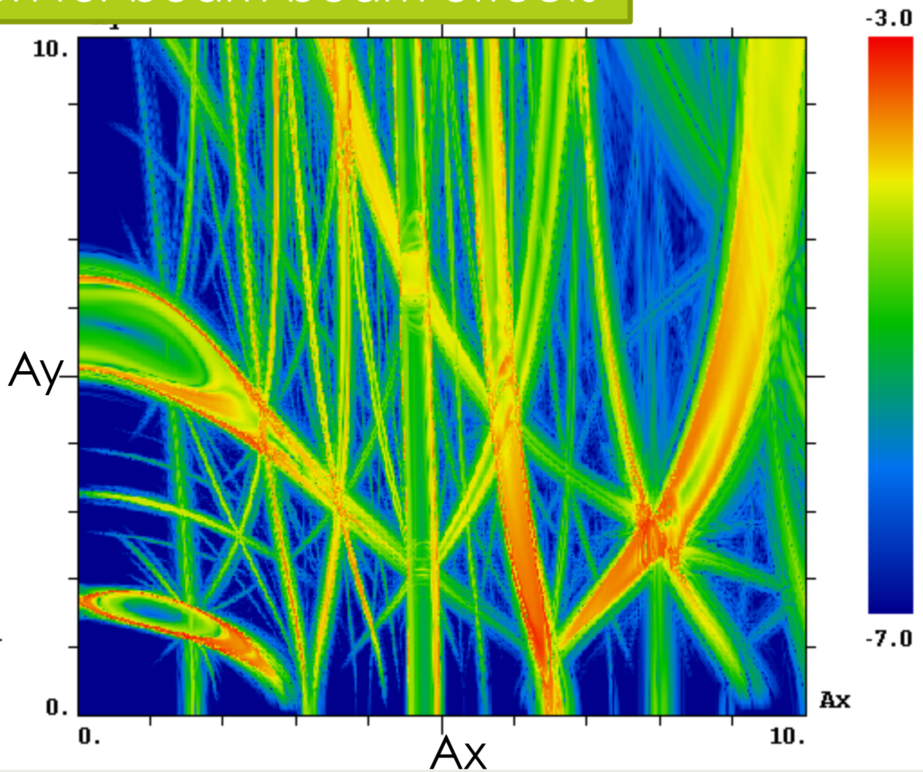
- Single and multi particle tracking
- Analysis methods
  - Evaluation of long-term particle motion stability
  - Resonance structure using Frequency Map Analysis
- Topics
  - Approximation of constantly varying V(s) with discrete thin elements
  - Effect of perturbations of T-insert lattice (non-equal β-functions, phase advance $\neq \pi$)
  - Effect of synchrotron oscillations
  - Sextupoles in the lattice
  - Alignment errors

Frequency Map Analysis

- Based on precise tune determination from FFT of turn-by-turn particle coordinate (2D tracking)
- Evaluate tune jitter in sliding time window ➔ resonances

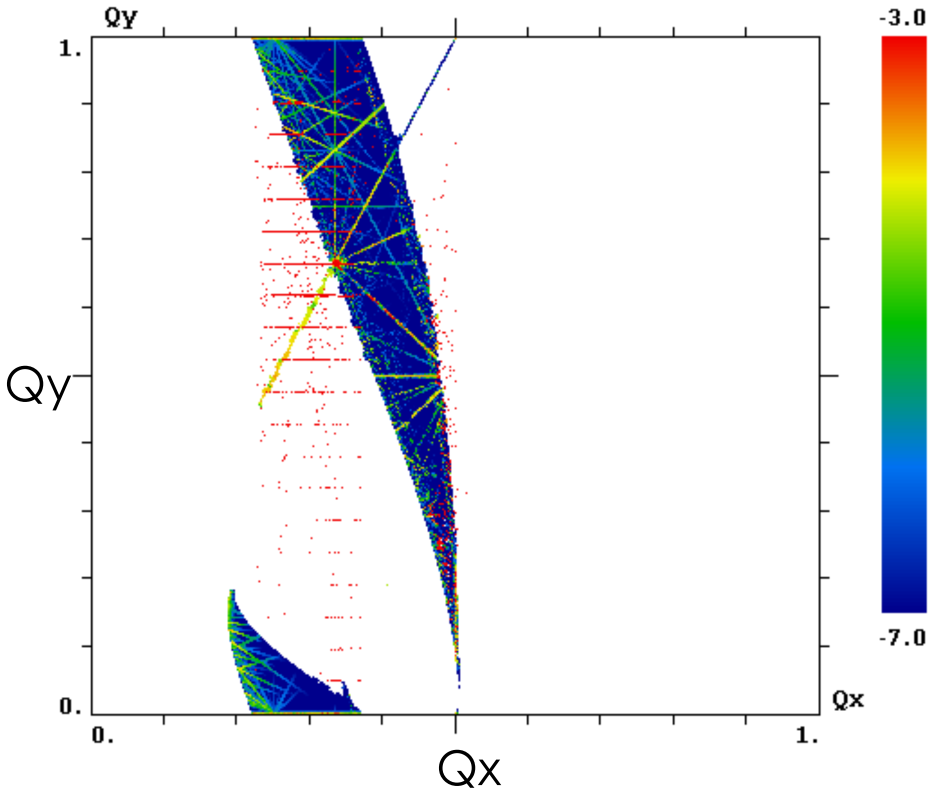
Example of FMA application for beam-beam effects

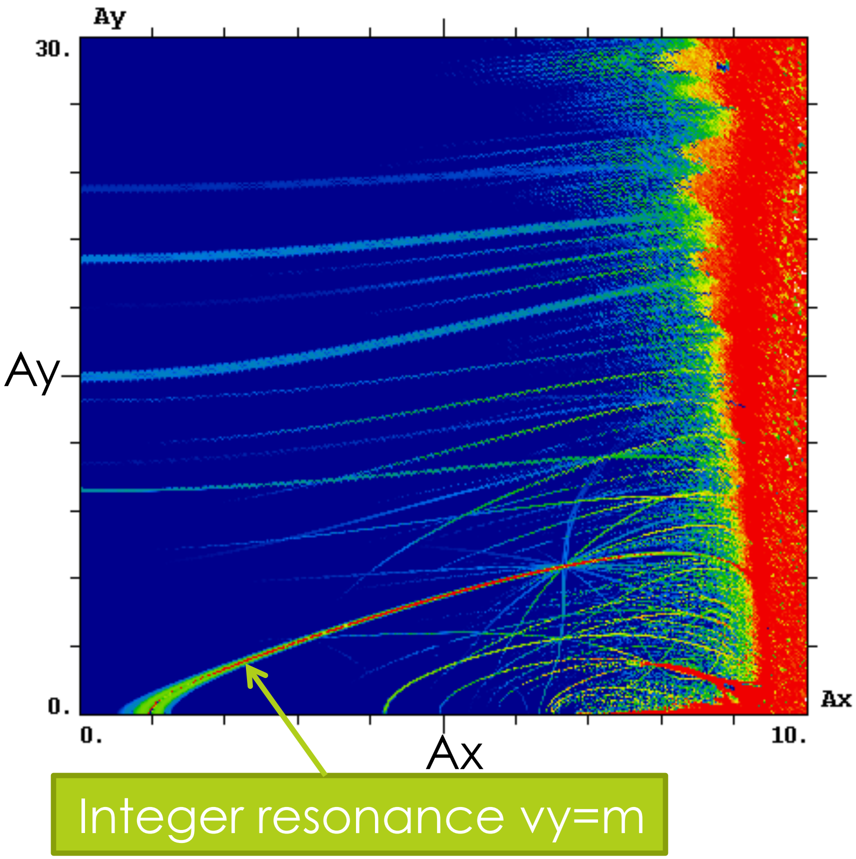




FMA of Integrable Optics

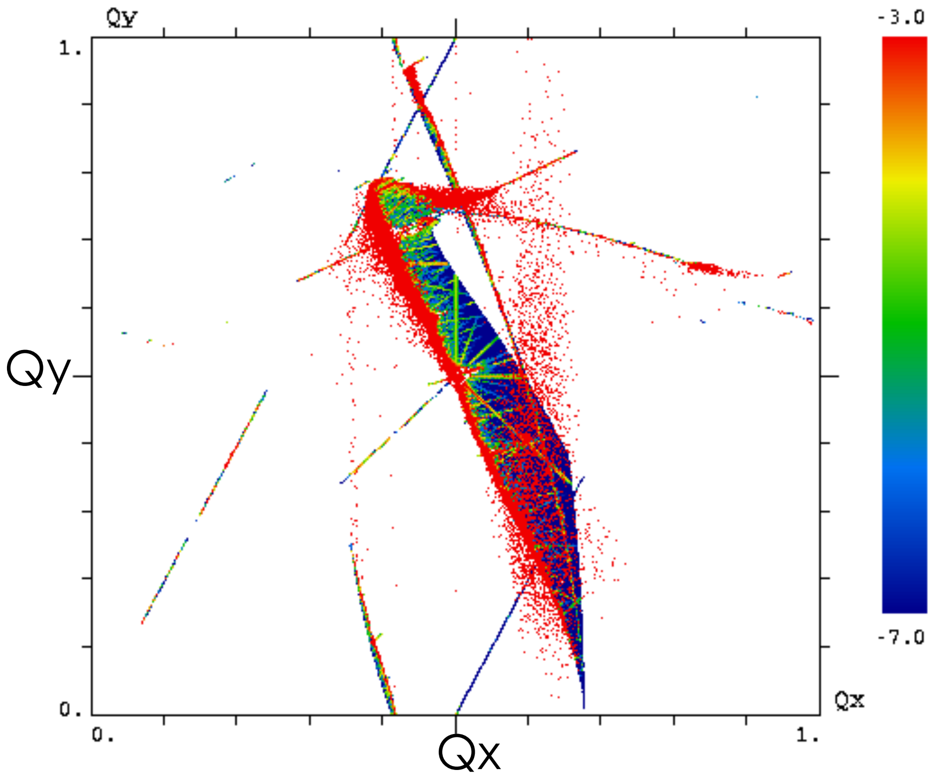
- ν_0=0.3, *t*=0.15, 40 thin elements per drift, 4 elements of periodicity

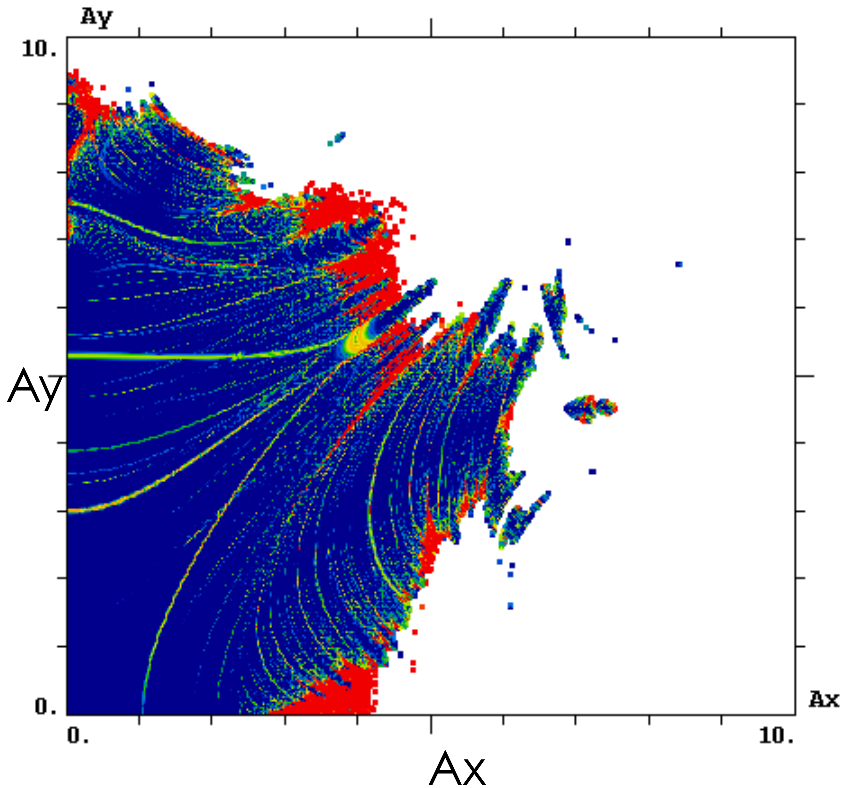




Integrable Optics vs. Conventional Multipoles

- Nonlinear potential approximated by multipole expansion up to 9th order



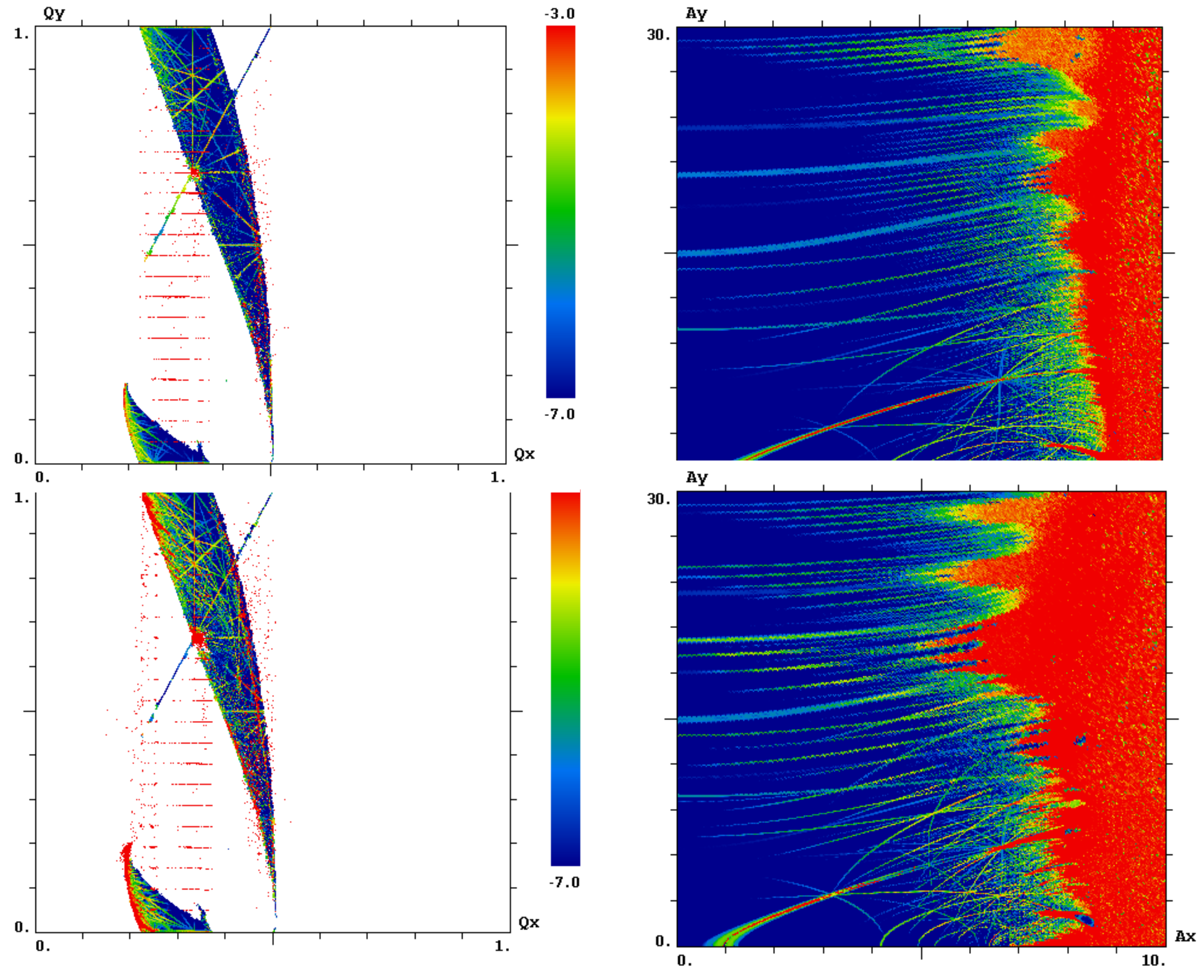


Effect of Number of Elements

- s-dependence of nonlinear potential approximated by N thin lenses

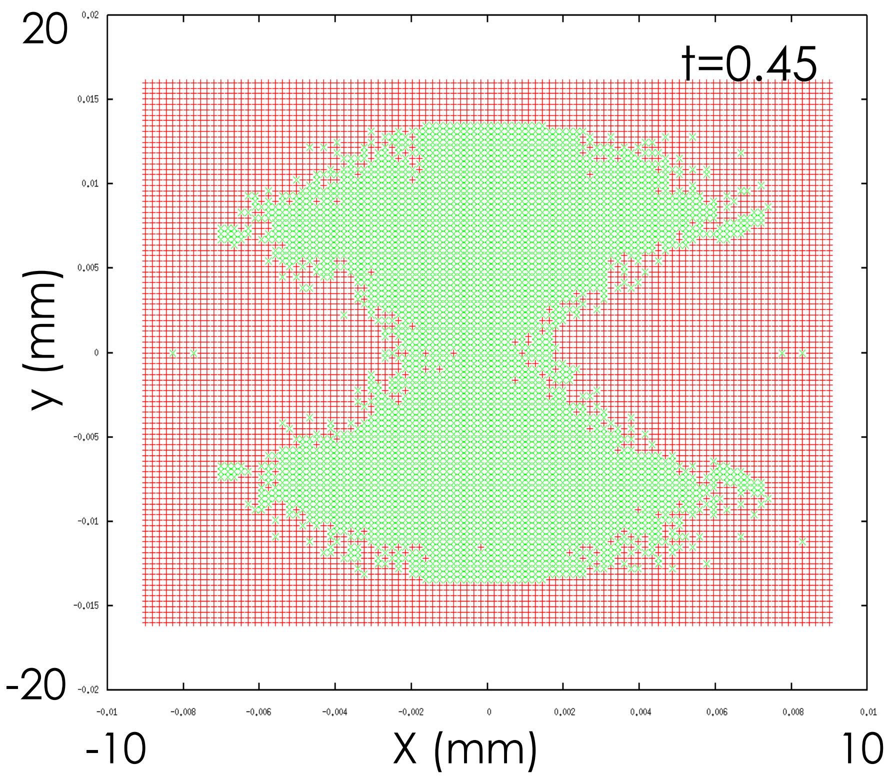
N = 20

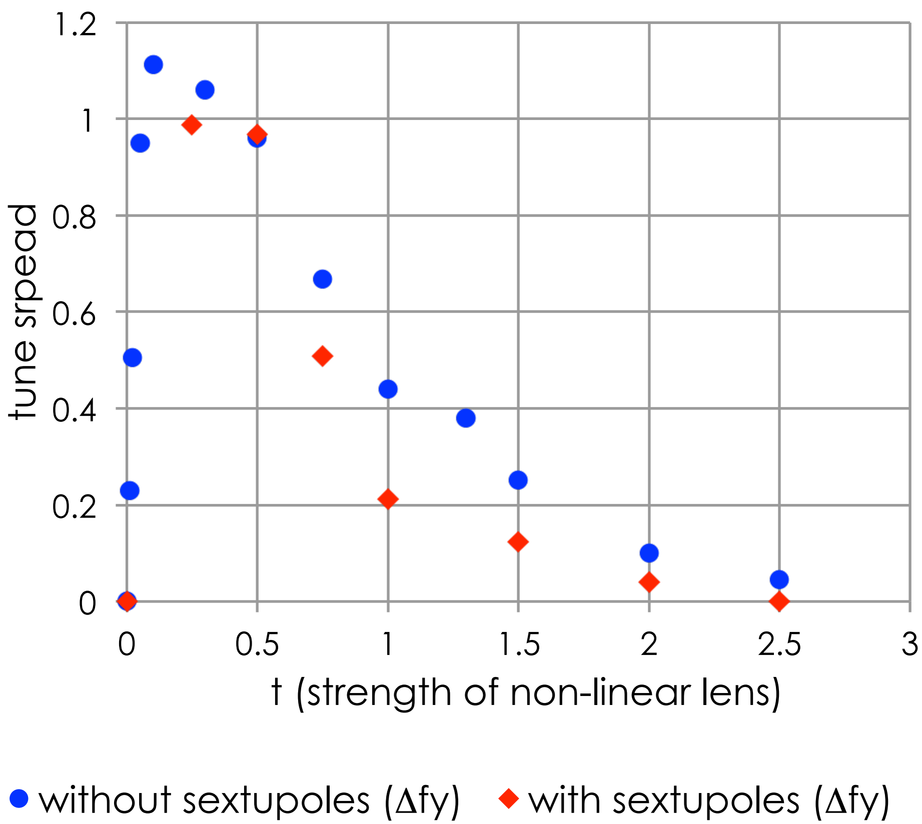
N = 10



Long-Term Tracking

- Track a bunch of macro-particles in integrable lattice with aperture limitations + chromaticity sextupoles





Integrable Optics Test Accelerator
Motivation

- An experimental test of the idea would benefit the worldwide accelerator physics community as well as the field of nonlinear dynamics in general
- Fermilab has a unique opportunity to take lead in this research as ASTA provides means to perform the experiment quickly and at low cost
- The ring can be used to perform other advanced accelerator R&D

IOTA Goals

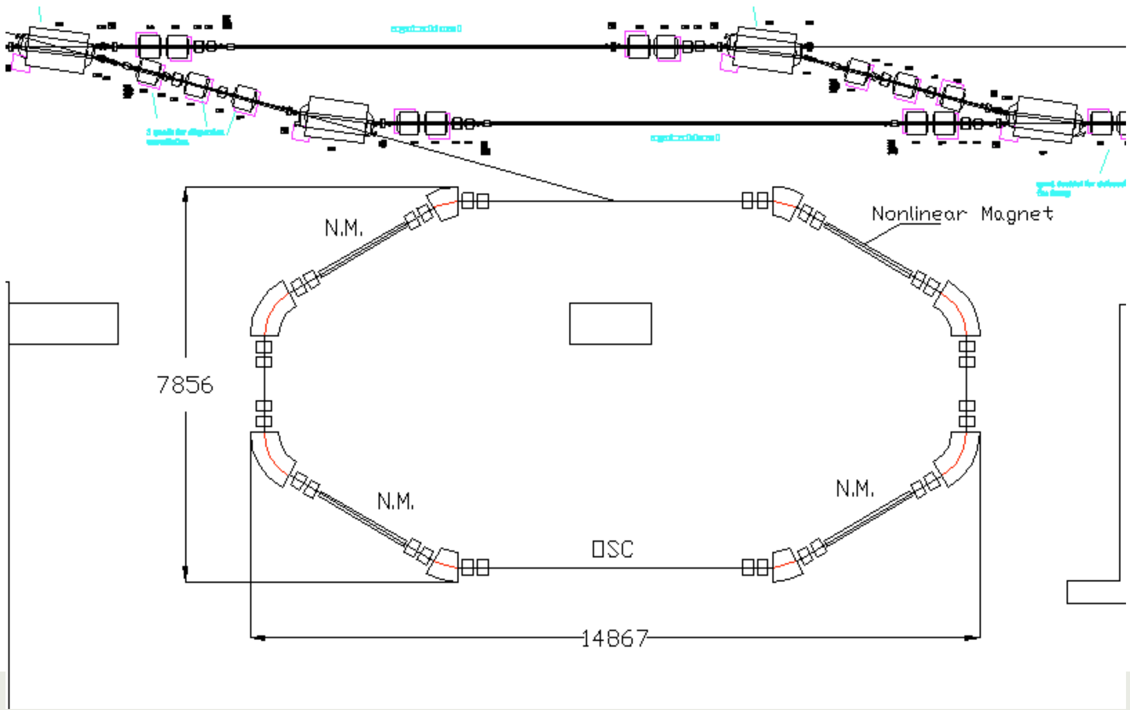
- We are constructing the Integrable Optics Test Accelerator ring, which would use the beam from e^- SRF linac with the ***goal to demonstrate the possibility to implement nonlinear integrable optics in a realistic accelerator design***
  - Only concentrate on the academic aspect of single-particle motion stability, leaving the studies of collective effects and attainment of high beam current to future research
  - Achieve large nonlinear tune shift/spread without degradation of dynamic aperture by "painting" the accelerator aperture with a "pencil" beam
  - Suppress strong lattice resonances = cross the integer resonance by part of the beam without intensity loss
  - Investigate stability of nonlinear system to perturbations
- The measure of success will be achievement of high nonlinear tune shift = 0.25

IOTA Goals 2

- After the proof-of-principle demonstration, further work will be directed towards
  - Achievement of large tune spread within a circulating beam
  - Achievement of space charge suppression in a nonlinear accelerator lattice
- We collaborate with ORNL, BINP, John Adams Institute (Oxford), TechX (SBIR phase 1) both on the current design and further development
- In addition to the primary goal, the ring can accommodate other Advanced Accelerator R&D experiments and/or users
  - Only portion of circumference is occupied with nonlinear magnets
  - Current design accommodates Optical Stochastic Cooling

IOTA Design. Lattice

- 4 elements of periodicity (cells)
- 2m drifts for practical nonlinear magnets
- T-insert tunable to allow a wide range of phase advances and beta-functions in the drift space in order to study different betatron tune working points
- One 5m-long straight section for the Optical Stochastic Cooling experiment.

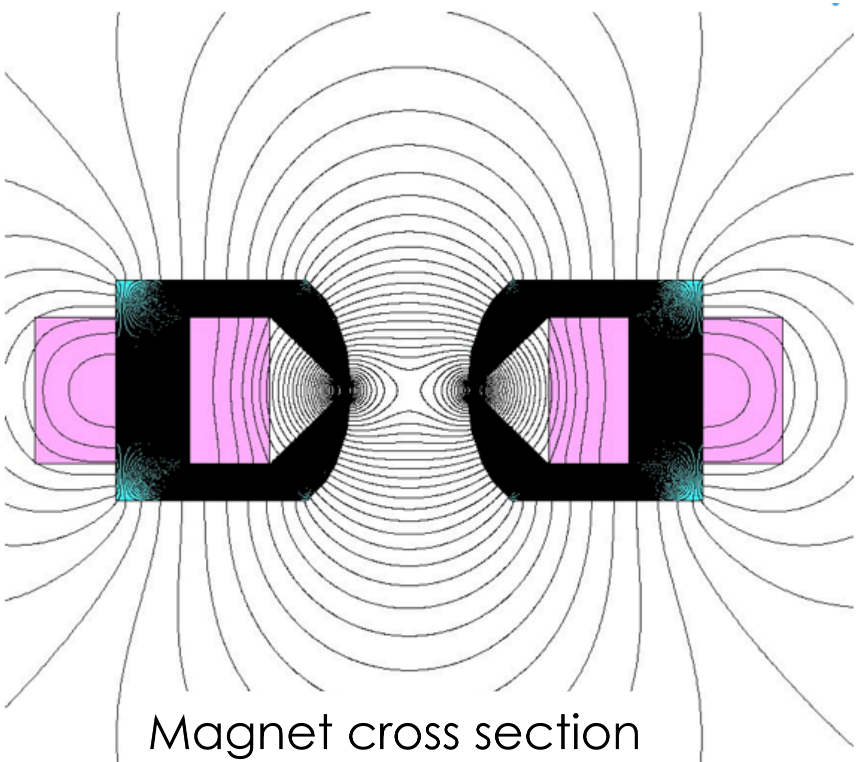


IOTA Design. Parameters

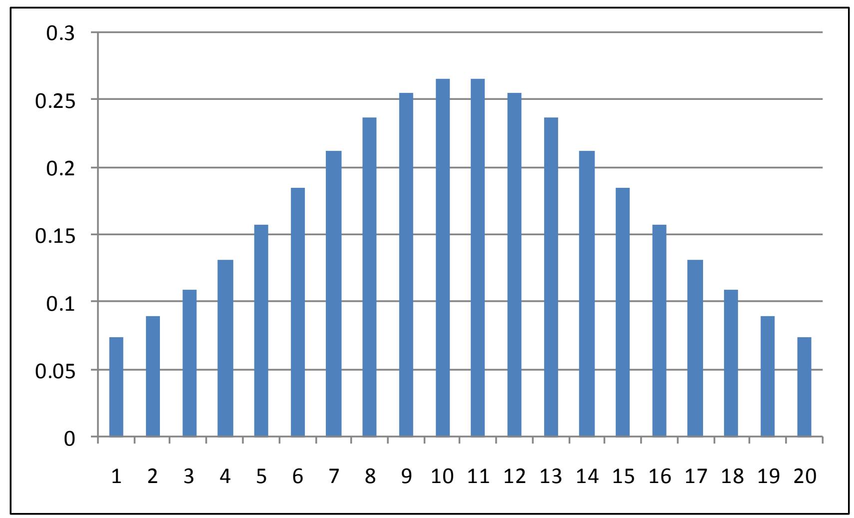
Parameter	Value
Electron beam energy	150 MeV
Circumference	30.4 m
Dipole field	0.5 T
RF voltage	50 kV
Maximum β-function	22 m
Momentum compaction	0.14
Betatron tune	$Q_x=Q_y=3.2$ (2.4 to 3.6)
Equilibrium transverse emittance r.m.s. non-normalized	0.06 μm
SR damping time	1s (10^7 turns)

IOTA Nonlinear Magnet FNAL Design

- Practical design – approximate continuously-varying potential with constant cross-section short magnets
- Horizontal aperture 1 cm



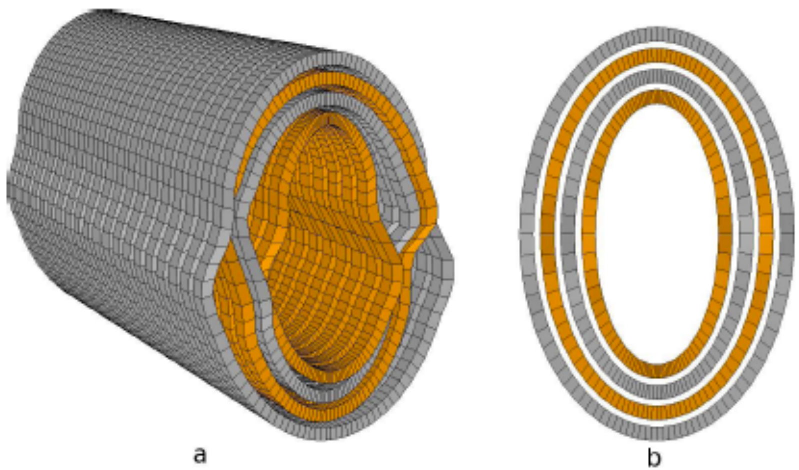
Magnet cross section
V.Kashikhin (FNAL)



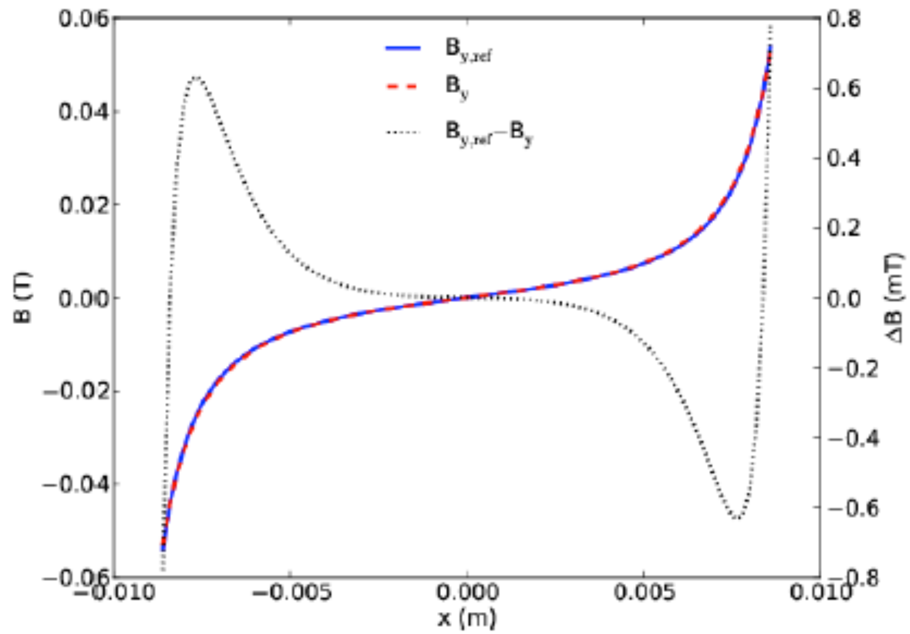
Quadrupole component of nonlinear field as function of s

Helical Coil Nonlinear Magnet JAI

- 3D design making use of modified helical coil method with two layers of conductor intersecting at an angle



Magnet cross section
(a) isometric perspective
(b) frontal view



Comparison of the desired and achieved vertical magnetic field on the centre plane

H.Witte, A.Seryi (JAI)

Status and Plans

- IOTA design requirements have been finalized
- Selected ring layout
- Dynamics simulations in the final lattice are in progress
- Procured components of beam instrumentation and vacuum systems

- Magnetic system specification early 2012
- Project review in 2012
- Component manufacture 2012
- Ring assembly 2013